Θ^+ baryon production in KN and NN reactions

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Abstract

We study $\Theta^+(1540)$ productions in kaon-nucleon (KN) and nucleon-nucleon (NN) interactions by assuming that the Θ^+ is an isosinglet with $J^P = \frac{1}{2}^+$. Possible t-channel diagrams with K^* exchange are considered in both reactions as well as K exchange in NN reaction. The cross section for $np \to \Lambda^0\Theta^+$, which has not been considered in previous calculations, is found to be about a factor of 5 larger than that for $np \to \Sigma^0\Theta^+$ due to the large coupling of $KN\Lambda$ interaction. The cross sections are obtained by setting $g_{KN\Theta} = 1$ and varying the ratio of $g_{K^*N\Theta}/g_{KN\Theta}$ so that future experimental data can be used to estimate these couplings. We also find that the isospin relations hold for these reactions.

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I. INTRODUCTION

The first experimental observation of a pentaquark baryon, the $\Theta^+(1540)$, was made in photon-nucleus reaction [1]. Later, the existence of the Θ^+ was confirmed by the analyses on kaon-nucleus [2], photon-deuteron [3], photon-proton [4, 5], and neutrino-nucleon reactions [6]. Till now, only the upper bound of the $\Theta^+(1540)$ decay width is known, it is around 9-25 MeV. Because of its positive strangeness, the minimal quark content of the $\Theta^+(1540)$ is $uudd\bar{s}$ and thus has hypercharge $Y = 2$. This means that the Θ^+ cannot be a three-quark state, and hence should be an exotic [7]. Such a narrow pentaquark state was predicted by chiral soliton model [8, 9]. There, the Θ^+ is an isosinglet and forms a baryon anti-decuplet with other pentaquark states, which is also anticipated in the Skyrme model [10–12]. If we consider baryons consisting of four quarks and one anti-quark, the flavor SU(3) group structure says that such systems can form the multiplets of **35**, **27**, $\overline{\mathbf{10}}$, **10**, **8**, and **1**. If the $\Theta^+(1540)$ is an isosinglet, then it would be a member of the baryon anti-decuplet.[1] The recently observed $\Xi^{*--}(1862)$, which carries $S = -2$ and $Q = -2e$ [13], could be a member of the anti-decuplet as its minimal quark content is $dd\bar{u}ss$. Such a state was also predicted by quark models and soliton models as an $I = 3/2$ member of the baryon anti-decuplet. Therefore, if confirmed by other experiments, the observation of the $\Xi^*(1862)$ strongly supports the existence of baryon anti-decuplet with the *isoscalar* Θ^+. However the $I = 1/2$ and $I = 1$ members of the baryon anti-decuplet are under debate, since these are crypto-exotic states and cannot be distinguished from three-quark baryons by the quantum numbers. Therefore, identifying those members is strongly dependent on the structure of the low-lying pentaquark states. In Ref. [14], Jaffe and Wilczek suggested a diquark-diquark-antiquark picture for the pentaquark anti-decuplet. For physical states of the $I = 1/2$ and $I = 1$ baryons, they considered mixing with pentaquark octet and identified $N(1440)$ and $N(1710)$ as pentaquark states.[2] Further extensions of this picture for pentaquark baryons can be found e.g., in Refs. [16–19]. Other theoretical investigations on the Θ^+ and/or baryon anti-decuplet can be found, e.g., in Refs. [20–40].

The production of the Θ^+ can also be investigated in heavy-ion collisions as discussed in Refs. [41–43]. In Ref. [41], a statistical model is used to predict that the Θ^+ yield is about 12-14% of the Λ yield in heavy-ion collisions. The dependence of the yield on the collision energy was discussed in Ref. [43]. Moreover, in Ref. [42], it was claimed that Θ^+ production can be a useful probe of the initially produced quark-gluon plasma state, because the number of the Θ^+ formed in the quark-gluon plasma can be non-trivial and the final state interaction through the hadronic phase is not large. However, as emphasized in Ref. [42], such claims depend crucially on understanding the strength of the hadronic interactions of the Θ^+. Thus investigating the hadronic interaction of the Θ^+ is important not only in understanding its structure but also in probing heavy-ion collisions.

The elementary production processes of the Θ^+ baryon have been investigated by several groups. In Refs. [44, 45], Lin and Ko estimated the total cross sections of Θ^+ production in photon-nucleon, meson-nucleon, and nucleon-nucleon reactions. It is further improved by including the anomalous magnetic moment interaction terms for γn reaction in Ref. [46]. In Ref. [47], we have reported the total and the differential cross sections for γp, γn, and πN

[1] The **35**-plet contains isotensor Θ which has $I = 2$, while the $I = 1$ isovector Θ is a member of the **27**-plet.

[2] Recently, in a coupled channel model for πN scattering, the Jülich group claimed that the Roper $N(1440)$ might be a quasi-bound σN state instead of a genuine three-quark state [15].

reactions, which was an improvement over previous studies in that we consistently included K^* exchanges. Recently, Liu *et al.* considered the reaction of $\gamma p \to \pi^+ K^- \Theta^+$ [48]. Some polarization observables in Θ^+ photoproduction are also estimated in Ref. [49]. In this paper, as a continuation of our efforts to understand the Θ^+ production processes, we investigate its production in KN and NN reactions. These reactions were previously investigated in Ref. [44] for $KN \to \pi\Theta^+$ and $pp \to \Sigma^+\Theta^+$ reactions, and then the cross sections were isospin-averaged. We improve this calculation by considering the K^* exchanges and we also consider $np \to \Lambda\Theta$ reaction, which will be shown to have larger cross section than $np \to \Sigma\Theta$. In addition, we derive isospin relations for different isospin channels in KN and NN reactions.

As shown in Refs. [46–50], the production cross sections are strongly dependent on the quantum numbers of the Θ^+, which is an important issue to be resolved.[3] First, the spin of the Θ^+ is believed to be $\frac{1}{2}$ [14]. But the parity of the Θ^+ is still under debate. If we assume that every quark is in the S-wave ground state as in the usual three-quark baryons, the parity of the pentaquark ground state would be odd because of the existence of one antiquark. Some quark models [21, 39], QCD sum rules [31, 33], and lattice QCD [36, 37] support $J^P = \frac{1}{2}^-$. However it is also claimed that the state with antisymmetric spatial wavefunction should be the ground state [14], which is consistent with the soliton model predictions [8]. Furthermore, recent quark model studies show that the ground state is in a P-wave if one includes the orbital motion of the quarks, which makes the ground state have even parity [22, 51]. This is also consistent with the heavy pentaquark (Θ_c and Θ_b) study in the Skyrme model, which predicts that the ground state has $J^P = \frac{1}{2}^+$ while the state with $\frac{1}{2}^-$ is the first excited state [52]. Thus, in this paper, we assume that the $\Theta^+(1540)$ has $I = 0$ and $J^P = \frac{1}{2}^+$.

This paper is organized as follows. In Sect. II, we compute the total and differential cross sections for $KN \to \pi\Theta$ reaction. The cross sections for $NN \to Y\Theta$ is then obtained in Sec. III, with $Y = \Lambda^0$ and Σ. We shall find that the $\Lambda\Theta$ channel has larger cross sections than the $\Sigma\Theta$ channel by about a factor of 5. Section IV contains a summary and discussion.

II. $KN \to \pi\Theta^+$ REACTION

As we have discussed before, we assume that the Θ^+ is a $J^P = \frac{1}{2}^+$ isoscalar particle belonging to baryon anti-decuplet. Then in the case of KN reaction, we have four possible isospin channels in Θ^+ production,

$$\begin{aligned} &K^+ p \to \Theta^+ \pi^+, \qquad K^0 p \to \Theta^+ \pi^0, \\ &K^+ n \to \Theta^+ \pi^0, \qquad K^0 n \to \Theta^+ \pi^-. \end{aligned} \tag{1}$$

The possible tree diagrams for $K^+ p \to \pi^+ \Theta^+$ are shown in Fig. 1. Here we denote the momenta of the incoming kaon, outgoing pion, initial nucleon, and the final Θ^+ as k, q, p, and p', respectively. The Feynman diagrams for the other isospin channels can be obtained in the same way.

[3] In Refs. [46, 47], it is claimed that the magnitudes of the cross sections for $\gamma N \to K\Theta$ are strongly dependent on the parity of the Θ^+. The cross sections for odd-parity Θ^+ were shown to be much smaller than those for even-parity Θ^+ by an order of magnitude. It is also shown that the differential cross section would have different angular distribution for different parity of the Θ^+ depending on the coupling $g_{K^*N\Theta}$.

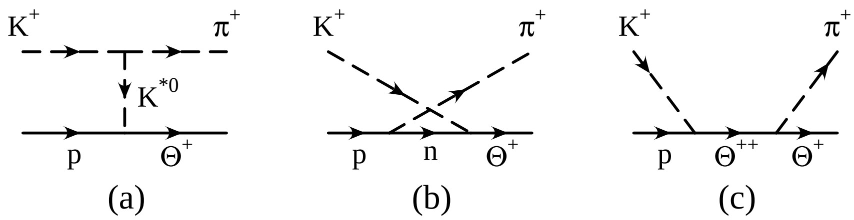

FIG. 1: Tree diagrams for $K^+p \to \pi^+\Theta^+$ reaction.

There are a few comments regarding the production mechanisms. First, in Ref. [44], the authors considered the diagram of Fig. 1(b). In this work, however, we extend the model of Ref. [44] by including t-channel K^* exchange, which allows the diagram of Fig. 1(a). As we shall see later, the contribution from the K^* exchange is non-trivial although its magnitude depends on the unknown coupling $g_{K^*N\Theta}$. A recent estimate on this coupling gives $g_{K^*N\Theta}/g_{KN\Theta} \sim 0.6$ [48]. If this is true, then the contribution from the K^* exchange should be important. Second, one may consider other nucleon or Δ excitations as an intermediate baryon state in Fig. 1(b). To begin with, the Δ excitation is excluded because of its isospin if the Θ^+ is an isosinglet. Furthermore, SU(3) symmetry does not allow the coupling of the anti-decuplet baryon with baryon decuplet and meson octet [16].[4] Other nucleon resonances such as the nucleon analog of the Θ^+ in the anti-decuplet can contribute through the diagram of Fig. 1(b). However, this brings in additional unknown coupling constant for antidecuplet-antidecuplet-octet interaction. Thus it will not be considered in this exploratory study. In Fig. 1(c), we have s-channel diagram which contains Θ^{++} as an intermediate state. If the Θ^{++} is an isovector particle, it can contribute to the production process. But if it is an isotensor particle, it cannot. Since the nature, mass, and couplings of the Θ^{++} are very unclear, we do not consider Fig. 1(c) in this paper.

We start with the SU(3) symmetric Lagrangian for the interactions of baryon anti-decuplet with meson octet and baryon octet [16],

$$\mathcal{L}_{\overline{D}PB} = -ig\bar{T}^{jkl}\gamma_5 P^j_m B^k_n \epsilon^{lmn} + \text{H.c.}, \tag{2}$$

where T^{ijk} is the baryon anti-decuplet, P^j_m the pseudoscalar meson octet, and B^k_n the baryon octet. This leads to

$$\begin{aligned}\mathcal{L}_{KN\Theta} &= -ig_{KN\Theta}\bar{\Theta}\gamma_5\bar{K}^c N + \text{ H.c.} \\ &= -ig_{KN\Theta}\left(\bar{\Theta}\gamma_5 K^+ n - \bar{\Theta}\gamma_5 K^0 p\right) + \text{ H.c.},\end{aligned} \tag{3}$$

where

$$N = \begin{pmatrix} p \\ n \end{pmatrix}, \qquad K^c = \begin{pmatrix} -\bar{K}^0 \\ K^- \end{pmatrix}. \tag{4}$$

The coupling $g_{KN\Theta}$ is related to the universal coupling constant g by $g_{KN\Theta} = \sqrt{6}g$. The effective Lagrangian for $K^*N\Theta$ interaction can be obtained in the same way,

$$\mathcal{L}_{K^*N\Theta} = -g_{K^*N\Theta}\left(\bar{\Theta}\gamma_\mu K^{*+\mu} n - \bar{\Theta}\gamma_\mu K^{*0\mu} p\right) + \text{ H.c.}, \tag{5}$$

[4] If the observed $\Theta^+(1540)$ is an isotensor particle [53], it should be a member of the **35** multiplet [54]. Then it has very different selection rules [55] and only the diagram of Fig. 1(b) with the Δ excitation as an intermediate state is allowed for its production from KN reactions with two-body final state. Diagrams like Figs. 1(a,c) are forbidden by isospin in this case.

where we have dropped tensor coupling terms as in Ref. [47].

The other effective Lagrangians necessary for $KN \to \pi N$ reaction are

$$\begin{aligned}
\mathcal{L}_{\pi NN} &= \frac{g_{\pi NN}}{2M_N}\bar{N}\gamma^\mu\gamma_5\partial_\mu\pi N, \\
\mathcal{L}_{K^*K\pi} &= -ig_{K^*K\pi}\left(\bar{K}\partial^\mu\pi K^*_\mu - \partial^\mu\bar{K}\pi K^*_\mu\right) + \text{ H.c..}
\end{aligned} \tag{6}$$

Here, we follow the prescription, e.g., of Ref. [56], namely, we use pseudovector coupling for pion interactions and pseudoscalar coupling for the interactions involving strangeness. The production amplitude for Fig. 1 is given by

$$\mathcal{M}_{K^+p\to\pi^+\Theta^+} = \bar{u}_\Theta(p')\,\mathcal{M}\,u_p(p), \tag{7}$$

where

$$\begin{aligned}
\mathcal{M}^{(1a)}_{K^+p} &= \frac{\sqrt{2}g_{K^*K\pi}g_{K^*N\Theta}}{(k-q)^2-M^2_{K^*}}\left\{\not{k}+\not{q}-\frac{1}{M^2_{K^*}}(M^2_K-M^2_\pi)(\not{k}-\not{q})\right\}, \\
\mathcal{M}^{(1b)}_{K^+p} &= -\frac{\sqrt{2}g_{KN\Theta}g_{\pi NN}}{2M_N\{(p-q)^2-M^2_N\}}\left\{\not{q}-\not{p}+M_N\right\}\not{q}.
\end{aligned} \tag{8}$$

Each vertex has a form factor in the form of

$$F(r, M_{\rm ex}) = \frac{\Lambda^4}{\Lambda^4+(r-M^2_{\rm ex})^2}, \tag{9}$$

where $M_{\rm ex}$ and r are the mass and the momentum squared of the exchanged particle, respectively. The value of the cutoff parameter Λ will be discussed later.

For the coupling constants, we use the well-known value for $g_{\pi NN}$ as $g^2_{\pi NN}/(4\pi) = 14.0$. The K^* decaying into $K\pi$ then yields $g_{K^*K\pi} = 3.28$, which is close to the SU(3) symmetry value, 3.02. The coupling $g_{KN\Theta}$ can be, in principle, determined from the decay width of $\Theta \to KN$. However, at this moment, only its upper bound is known from experiments, 9–25 MeV. Theoretically, the chiral soliton model predicted 15 MeV in Ref. [8], which was later improved to be about 5 MeV [9]. If we assume that the Θ^+ decay width is 5 MeV, then we have $g_{KN\Theta} = 2.2$ [47]. Recent analyses on KN elastic scattering data favor such a small decay width of the Θ^+ [57, 58] or a smaller decay width, namely 1 MeV or even less [59].[5] There is only one experimental information about the total cross section of Θ^+ production in γp reaction near threshold [4], which, however, should be confirmed by further analyses [60]. Therefore in this paper, we do not try to fix $g_{KN\Theta}$. Instead, we give the results with $g_{KN\Theta} = 1$ so that future experimental data can be used to estimate the coupling constants with our predictions. We also note that $g_{KN\Theta} = 1$ corresponds to $\Gamma(\Theta) \approx 1.03$ MeV. We also point out that the Θ couplings to K^+n and K^0p have different phase, which differs from Ref. [8]. Our convention is consistent with the SU(3) symmetry for the anti-decuplet [16] and is crucial to obtain the isospin relations (10). Finally for $g_{K^*N\Theta}$, there is no information for this coupling. In Ref. [47], we have mentioned that precise measurements on the differential cross sections for γN and πN reactions can be used to estimate this coupling. Recently it was estimated to be $g_{K^*N\Theta}/g_{KN\Theta} \sim 0.6$ based on some theoretical assumptions [48]. Because

[5] No evidence for Θ^{++} in the existing data for K^+p channel was also reported in Ref. [59].

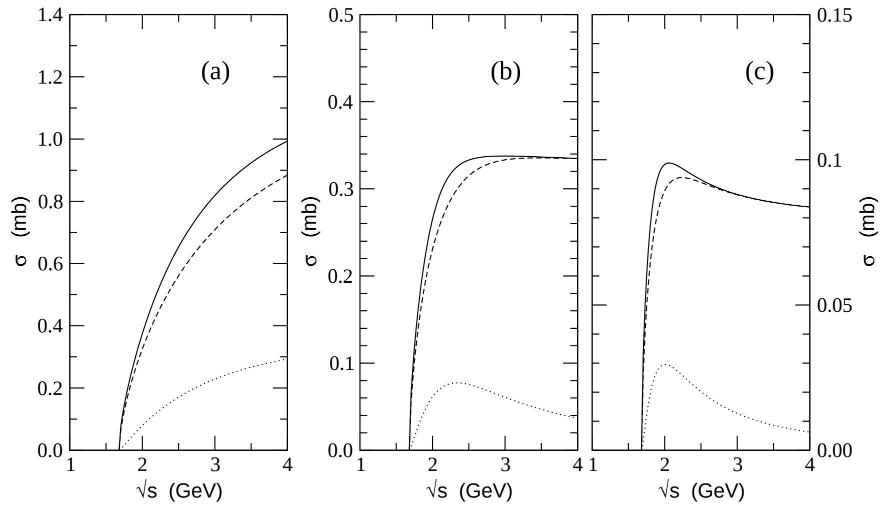

FIG. 2: Total cross sections for $K^+p \to \pi^+\Theta^+$ (a) without form factor, (b) with form factor (9) and $\Lambda = 1.8$ GeV, (c) with $\Lambda = 1.2$ GeV. The solid lines are obtained with $g_{K^*N\Theta} = +g_{KN\Theta}$, the dotted lines are with $g_{K^*N\Theta} = 0$, and the dashed lines are with $g_{K^*N\Theta} = -g_{KN\Theta}$.

of the lack of precise information, however, we treat $g_{K^*N\Theta}$ as a free parameter and give the results by varying its value as we did in Ref. [47]. It should be also noted that the $K^*N\Theta$ interaction contains tensor coupling. The contribution from this term should be examined but will not be discussed in this qualitative study.

The other isospin channels can also be calculated using the effective Lagrangians above, and it is straightforward to find the following isospin relation,[6]

$$\mathcal{M}_{K^+p} = -\mathcal{M}_{K^0n} = -\sqrt{2}\mathcal{M}_{K^0p} = -\sqrt{2}\mathcal{M}_{K^+n}. \tag{10}$$

Note that the different phase between the $\bar{\Theta}K^+n$ and $\bar{\Theta}K^0p$ interactions is essential to have the above relation. In this paper, we give the results for the K^+p reaction only. Cross sections for the other isospin channels can then be read from our result by using the isospin relation above.

The total cross section for $K^+p \to \pi^+\Theta^+$ is plotted in Fig. 2. Since we do not have any experimental information, we first present the result without form factor in Fig. 2(a). The results with the form factor (9) are then given in Figs. 2(b,c) with $\Lambda = 1.8$ GeV and 1.2 GeV, respectively. The cutoff parameter $\Lambda = 1.8$ GeV is from kaon photoproduction analyses [61], while $\Lambda = 1.2$ GeV is from πN scattering analyses [56]. Here, the solid lines are obtained with $g_{K^*N\Theta} = +g_{KN\Theta}$, the dotted lines are with $g_{K^*N\Theta} = 0$, and the dashed lines are with $g_{K^*N\Theta} = -g_{KN\Theta}$.

Differential cross section for $K^+p \to \pi^+\Theta^+$ is shown in Fig. 3 at $\sqrt{s} = 2.4$ GeV as a function of the scattering angle θ in the CM frame, where θ is defined by the directions of $\mathbf{k}$ and $\mathbf{q}$. Here again, we give the results with different cutoff Λ. Figure 3 shows the role of the K^* exchanges in a transparent way. Without K^* exchange, we have the u-channel diagram only [Fig. 1(b)] whose results are given by the dotted lines in Fig. 3. They are

[6] In the reactions of K^+n and K^0p, one may consider diagrams like Fig. 1(c) with the Θ^+ as the intermediate state. However, these diagrams are not allowed since the $\Theta\Theta\pi$ interaction is prohibited by isospin.

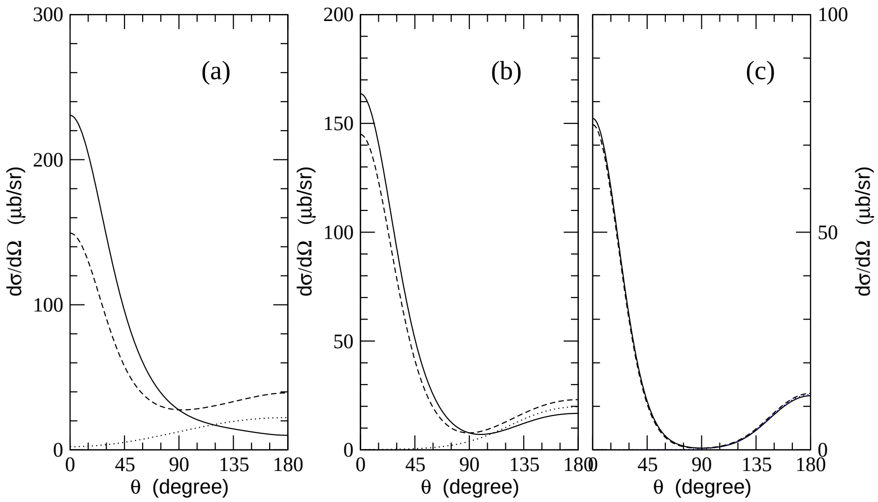

FIG. 3: Differential cross sections for $K^+p \to \pi^+\Theta^+$ at $\sqrt{s} = 2.4$ GeV (a) without form factor, (b) with form factor (9) and $\Lambda = 1.8$ GeV, (c) with $\Lambda = 1.2$ GeV. The dotted line in (c) is almost overlapped with other lines (so it is not distinguishable) at $\theta \geq 90°$. It is also suppressed in the other region and is not seen in (c). The notations are the same as in Fig. 2.

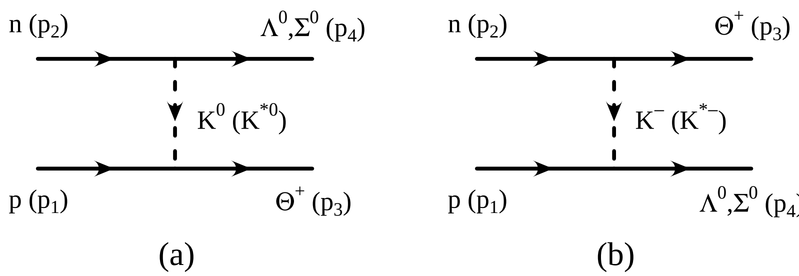

FIG. 4: Tree diagrams for $np \to \Sigma^0(\Lambda^0)\Theta^+$ reaction.

peaked at backward scatting angles. With K^* exchanges, the differential cross sections (the dashed and solid lines) have additional peaks at forward angles. Thus, the forward peaks in Fig. 3 are purely developed from the K^* exchange and can be larger than the backward peak depending on $g_{K^*N\Theta}/g_{KN\Theta}$. So Measurements of differential cross section can give informations on the magnitude of the coupling $g_{K^*N\Theta}$, which cannot be estimated from the Θ^+ decay width. But we find that the phase of $g_{K^*N\Theta}/g_{KN\Theta}$ cannot be distinguished in these results.

III. $NN \to Y\Theta^+$ REACTION

In this Section, we investigate $NN \to Y\Theta$ reactions where Y stands for Σ or Λ baryons. The $pp \to \Sigma^+\Theta^+$ process was considered within K exchange model in Ref. [44]. Here we give more extensive calculation by including K^* exchanges. We also study $np \to \Lambda^0\Theta^+$ reaction which was not considered in Ref. [44]. To calculate the cross sections, we need additional Lagrangians besides $\mathcal{L}_{KN\Theta}$ and $\mathcal{L}_{K^*N\Theta}$ given in Eqs. (3) and (5), which are

$$\mathcal{L}_{KNY} = -ig_{KNY}\bar{N}\gamma_5 YK + \text{ H.c.},$$

$$\mathcal{L}_{K^*NY} = -g_{K^*NY}\bar{Y}\gamma_\mu \bar{K}^{*\mu} N - \frac{g^T_{K^*NY}}{M_Y + M_N}\partial^\nu \bar{K}^{*\mu}\bar{Y}\sigma_{\mu\nu}N + \text{ H.c.,} \tag{11}$$

where $Y = \Lambda, \mathbf{\Sigma}\cdot\boldsymbol{\tau}$. For g_{KNY}, we use the SU(3) symmetry values,

$$g_{KN\Lambda} = -\frac{1}{\sqrt{3}}g_{\pi NN}(1+2f), \qquad g_{KN\Sigma} = g_{\pi NN}(1-2f), \tag{12}$$

which leads to

$$g_{KN\Lambda}/\sqrt{4\pi} = -3.74, \qquad g_{KN\Sigma}/\sqrt{4\pi} = 1.00, \tag{13}$$

with $d + f = 1$ and $f/d = 0.575$. These values are within the range of phenomenological values [62],

$$g_{KN\Lambda}/\sqrt{4\pi} = -4.49 \sim -3.46, \qquad g_{KN\Sigma}/\sqrt{4\pi} = 1.32 \sim 1.02. \tag{14}$$

The K^*NY couplings are estimated in Refs. [62, 63]. For example, the new Nijmegen potential gives [62]

$$\begin{aligned} g_{K^*N\Lambda} &= -6.11 \sim -4.26, \qquad & g^T_{K^*N\Lambda} &= -14.9 \sim -11.3, \\ g_{K^*N\Sigma} &= -3.52 \sim -2.46, \qquad & g^T_{K^*N\Sigma} &= 4.03 \sim 1.15. \end{aligned} \tag{15}$$

In our numerical calculation, we use

$$g_{K^*N\Lambda} = -4.26, \qquad g^T_{K^*N\Lambda} = -11.3, \qquad g_{K^*N\Sigma} = -2.46, \qquad g^T_{K^*N\Sigma} = 1.15. \tag{16}$$

The transition amplitudes for $np \to \Sigma^0\Theta^+$ obtained from Fig. 4 read

$$\mathcal{M}^K_{np} = -\frac{g_{KN\Sigma}g_{KN\Theta}}{(p_2 - p_4)^2 - M_K^2}\bar{u}(p_4)\gamma_5 u(p_2)\,\bar{u}(p_3)\gamma_5 u(p_1) + (p_1 \leftrightarrow p_2), \tag{17}$$

for K exchange and

$$\begin{aligned} \mathcal{M}^{K^*}_{np} &= -\frac{g_{K^*N\Theta}}{(p_2 - p_4)^2 - M^2_{K^*}}\left\{g^{\mu\nu} - \frac{1}{M^2_{K^*}}(p_4 - p_2)^\mu (p_4 - p_2)^\nu\right\} \\ &\quad \times \bar{u}(p_4)\Gamma^{K^*N\Sigma}_\nu (p_4 - p_2)u(p_2)\,\bar{u}(p_3)\gamma_\mu u(p_1) + (p_1 \leftrightarrow p_2), \end{aligned} \tag{18}$$

for K^* exchange with

$$\Gamma^{K^*N\Sigma}_\nu (p_4 - p_2) = g_{K^*N\Sigma}\gamma_\nu - i\frac{g^T_{K^*N\Sigma}}{M_\Sigma + M_N}\sigma_{\nu\alpha}(p_4 - p_2)^\alpha. \tag{19}$$

The momenta of the particles are defined in Fig. 4.

The other isospin reactions, $pp \to \Sigma^+\Theta^+$ and $nn \to \Sigma^-\Theta^+$, have the following relation,

$$\mathcal{M}_{pp} = -\mathcal{M}_{nn} = -\sqrt{2}\mathcal{M}_{np}. \tag{20}$$

Since the cross sections for $pp \to \Sigma^+\Theta^+$ and $nn \to \Sigma^-\Theta^+$ reactions can be read off from that for $np \to \Sigma^0\Theta^+$ by the above relation, we give the results for np reactions only.

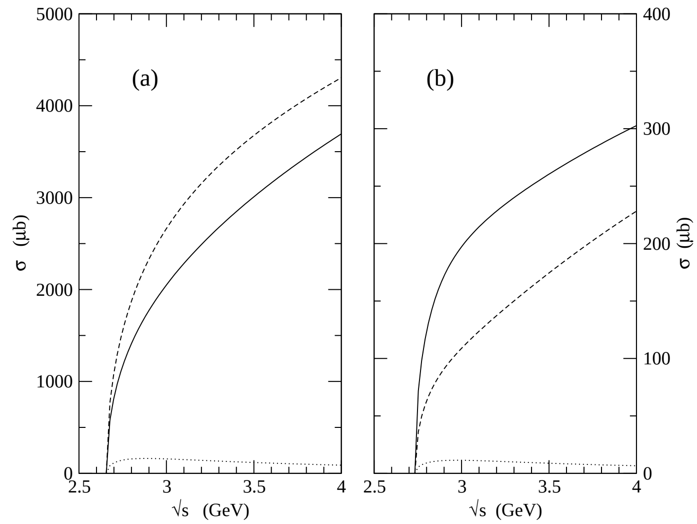

FIG. 5: Total cross sections for (a) $np \to \Lambda^0\Theta^+$ and (b) $np \to \Sigma^0\Theta^+$ without form factors. The notations are the same as in Fig. 2.

In np reaction, we have an additional channel in the final state, i.e., $np \to \Lambda^0\Theta^+$. The production amplitudes of this reaction read

$$
\begin{aligned}
\mathcal{M}^{K}_{np\to\Lambda^0\Theta^+} &= \frac{g_{KN\Lambda}g_{KN\Theta}}{(p_2-p_4)^2-M_K^2}\bar{u}(p_4)\gamma_5 u(p_2)\,\bar{u}(p_3)\gamma_5 u(p_1) + (p_1 \leftrightarrow p_2),\\
\mathcal{M}^{K^*}_{np\to\Lambda^0\Theta^+} &= \frac{g_{K^*N\Theta}}{(p_2-p_4)^2-M_{K^*}^2}\left\{g^{\mu\nu} - \frac{1}{M_{K^*}^2}(p_4-p_2)^\mu(p_4-p_2)^\nu\right\}\\
&\quad \times \bar{u}(p_4)\Gamma^{K^*N\Lambda}_\nu(p_4-p_2)u(p_2)\,\bar{u}(p_3)\gamma_\mu u(p_1) + (p_1 \leftrightarrow p_2),
\end{aligned}
\tag{21}
$$

for K and K^* exchanges, where

$$
\Gamma^{K^*N\Lambda}_\nu(p_4-p_2) = g_{K^*N\Lambda}\gamma_\nu - i\frac{g^T_{K^*N\Lambda}}{M_\Lambda+M_N}\sigma_{\nu\alpha}(p_4-p_2)^\alpha. \tag{22}
$$

The form factor (9) is assumed to be multiplied to each vertex.

In Fig. 5, the total cross sections for $np \to \Lambda^0\Theta^+$ and $np \to \Sigma^0\Theta^+$ are given, which do not include the form factors. Shown in Fig. 6 are the results with the form factor (9) and $\Lambda = 1.2$ GeV. These results show that the K^* exchange dominates the process if $g_{K^*N\Theta}/g_{KN\Theta}$ is not so small. They also show that K and K^* exchanges have different energy dependence in the total cross sections.

The role of K^* exchange can also be identified in differential cross sections. Figures 7 and 8 show the differential cross sections at $\sqrt{s} = 3$ GeV without and with the form factors (with $\Lambda = 1.2$ GeV). The scattering angle θ is defined by the directions of $\mathbf{p}_1$ and $\mathbf{p}_3$ in CM frame. It is clearly seen from these figures that the differential cross sections have symmetric shape about $\theta = 90^\circ$ in both reactions, which can be expected from the structure of the production amplitudes, e.g., in Eq. (21) regardless of the exchanged meson. Since the ratio of the minimum and maximum values of the differential cross sections depends on the ratio of coupling constants, measurement of the ratio would shed light on the determination of the magnitude of $g_{K^*N\Theta}/g_{KN\Theta}$. But the results are nearly independent on the phase of $g_{KN\Theta}/g_{K^*N\Theta}$ (Fig. 8).

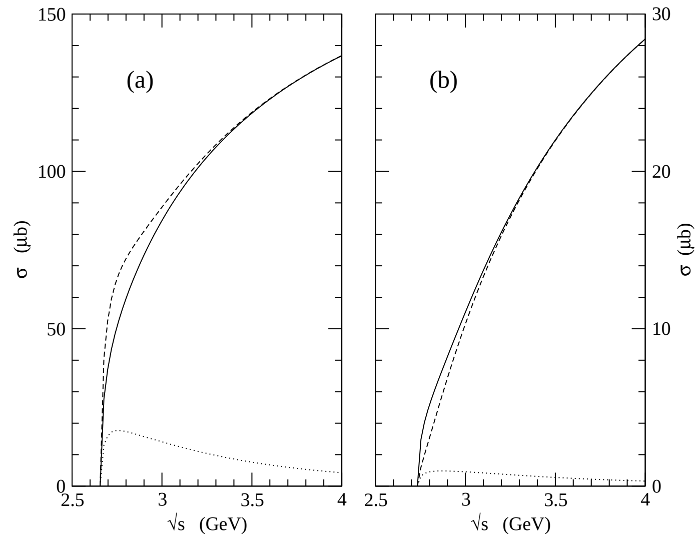

FIG. 6: Total cross sections for (a) $np \to \Lambda^0\Theta^+$ and (b) $np \to \Sigma^0\Theta^+$ with the form factor (9) and $\Lambda = 1.2$ GeV. The notations are the same as in Fig. 2.

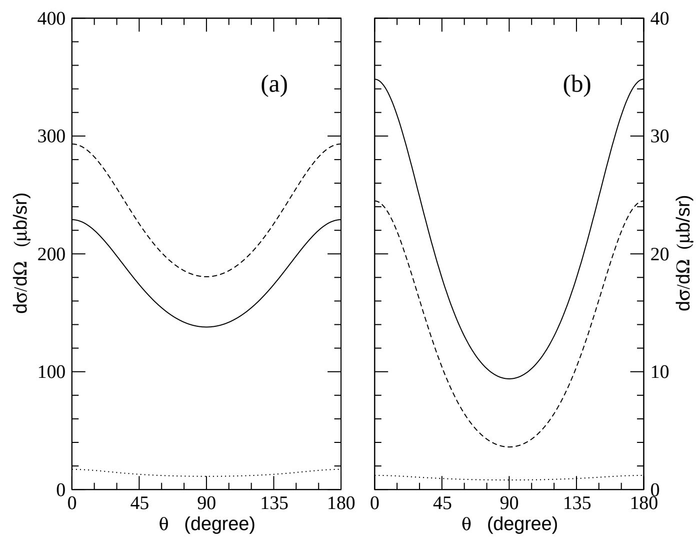

FIG. 7: Differential cross sections for (a) $np \to \Lambda^0\Theta^+$ and (b) $np \to \Sigma^0\Theta^+$ at $\sqrt{s} = 3$ GeV without form factors. The notations are the same as in Fig. 2.

IV. SUMMARY

We have estimated the cross sections for Θ^+ baryon production from KN and NN reactions focusing on the role of the K^* exchanges. We found that isospin relations hold in $KN \to \pi\Theta$ and $NN \to \Sigma\Theta$ reactions. We have also estimated the cross section for $np \to \Lambda^0\Theta^+$, which is found to be much larger than that for $np \to \Sigma^0\Theta^+$.

Without K^* exchange, we found that there is only a backward peak in the differential cross sections for KN reactions. The forward peak in Fig. 3 is completely ascribed to the K^* exchange. Thus precise measurements on the differential cross sections will give a chance to determine the magnitude of the $g_{K^*N\Theta}$ coupling. In NN reactions, we found that both K

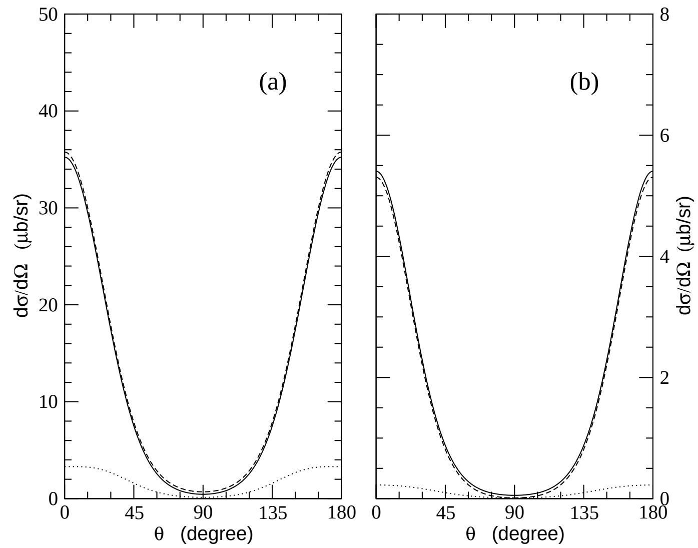

FIG. 8: Differential cross sections for (a) $np \to \Lambda^0\Theta^+$ and (b) $np \to \Sigma^0\Theta^+$ at $\sqrt{s} = 3$ GeV with the form factor (9) and $\Lambda = 1.2$ GeV. The notations are the same as in Fig. 2.

exchange and K^* exchange give double peaks, forward and backward peaks, and symmetric differential cross sections. Therefore, measuring the ratio of the maximum and minimum values of the differential cross sections can also give an information on the couplings.

As we have discussed, investigation of Θ^+ production processes in meson-nucleon and nucleon-nucleon reactions are useful in understanding the interactions and the production mechanisms of the Θ^+, as well as in providing an important information for the Θ^+ yield in heavy-ion collisions, where hadronic final state effects should be taken into account. Experimental studies on these reactions are, therefore, highly required and might be available at current experimental facilities.

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